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“Structure Formation in Complex Plasma”

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Submitted
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14. ABSTRACT **Complex plasma result when microparticle ?dust? becomes entrapped in a radio frequency (rf) discharge plasma. Dust charging was studied both theoretically and experimentally under cryogenic conditions whereby the charged microparticles experience supersonic flow in the presence of gravitational field. This research involved an investigation of microparticle structure formation in complex plasma under extreme conditions. A theoretical study of the charging mechanism in a non-uniform discharge plasma revealed that plasma density and temperature effects on dust grain charging at cryogenic temperatures is much smaller than that at the room temperature, which is in agreement with experimental observations. It is suggested that charging at cryogenic temperatures makes the formation of a strongly coupled system of dust particles.**					
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Abstract:
The research has been carried out at the Complex Plasma Lab of Yokohama National University in Yokohama, Japan (Director: Osamu Ishihara). A complex plasma is characterized by the charge neutrality of a plasma with microparticles and is termed as a complex system because of a collective nature produced by the interaction between plasma and charged microparticles. The cryogenic complex plasma experiment provides a unique environment of an ultracold plasma in a liquid helium vapor. Because of the temperature gradient between the rf discharge plasma and the liquid helium, the thermophoretic force acts on microparticles. The large area room temperature complex plasma experiment provides unique setting to produce supersonic flow of charged microparticles in the presence of gravitational force. Our study was motivated to produce extreme conditions for physical problems in the complex plasma. Structure formation of microparticles in the cryogenic environment and supersonic flow environment has been studied. Basic features of complex plasma in an ultracold plasma are characterized by the interaction of microparticles with cold neutral particles, while the shock formation was studied in detail in a supersonic complex plasma. Simulation study revealed the formation of double helix by microparticles confined in a plasma as a state of CME (configuration of minimum energy).

Introduction:

Small charged dust particles in plasmas are commonly observed in laboratory, in industrial applications and in space. They are round or irregularly shaped grains of carbon, silicates or other material on the order of a micron or a fraction of a micron across. Such small fine particles of micron sizes in space were studied by plasma physics pioneers Irving Langmuir (candle flame in 1920s), Lyman Spitzer (interstellar space in1940s) and Hannes Alfvén (planetary formation in 1950s). Much later, the interests in dusty plasmas got an attention through the observation in the processing in reactive plasmas in the semiconductor industry in 1980s. The research in contamination control revealed that the particulate contamination of silicon substrates was produced from the plasma itself rather than from the external contaminated air. The micron size particles known as dust particles were formed and grew in the gas through aggregation. They were forming a cloud electrically levitated above the wafer and fell on the wafer when the applied voltage on the wafer was turned off.

The Coulomb lattice discovered in 1994 forms regular structures of microparticles in a plasma. Experimental discoveries of Coulomb crystals in laboratory dusty plasmas rekindled the interest of Coulomb lattice formation and recent research on plasma crystallization includes the study of phase transitions, lattice defects and others. Since micron size dust particles in laboratory plasmas could accumulate thousands of electrons on the surface, the resulting Coulomb repulsion between charged dust grains is expected to be strong. A complex plasma als o known as dusty plasma is characterized by a complex system in which charged dust particles interact with plasmas.

Recent advances in the study of a complex plasma have been developed in space plasma, cosmic plasma, laboratory plasmas, fusion plasma as well as industrial plasmas. A cryogenic complex plasma is an emerging field to study dust-plasma interaction in such an extreme condition as cryogenic temperature. We also developed an experimental device to study the flow effects of microparticles levitated at the sheath. Our focus is the study of a complex plasma in extreme conditions one at the liquid helium temperature, and the other in a supersonic flow.

Personnel:

(1) Osamu Ishihara, a principal investigator and a director of the Complex Plasma Lab at Yokohama National University
(2) Dr. Yoshiharu Nakamura,[*1] a senior technical advisor, retired from ISAS (Institute of Space and Astronautical Science), JAXA (Japan Space Exploration Agency)
(3) Dr. Masako Shindo, a research associate
(4) Dr. Yoshifumi Saitou, a research associate

(5) Dr. Nirab Adhikary,[*1] a postdoctoral fellow
(6) Ms. Natsuko Uotani,*[2] a graduate student who completed her master degree in March, 2011 with the thesis Charging and dynamic behavior of microparticles in a cryogenic plasma –two dimensional structure formation –
(7) Ms. Megumi Chikasue,*[2] a graduate student who continues her graduate study after completion of her senior thesis (Thermophoretic force in a cryogenic complex plasma) in March, 2011
(8) Ms. Naomi Shibuya,[*1] secretary
*1 salary is paid by the grant
*2 research assistantship

Experiment:

(1)YD-1 Experiment (Conference proceedings 1,2; Presentations 1,2,6)

Experimental setup YD-1 is a glass tube contained in a silver-coated glass Dewar bottle (glass cryostat) with the inner diameter of 9.6 cm and the height of 80 cm (Figure 1). The Dewar bottle is filled with liquid helium or liquid nitrogen and is inserted in a liquid nitrogen stored in an outer Dewar bottle with the outer diameter of 20 cm. The silver coated Dewar bottles have 1 cm wide vertical uncoated slit for observational purpose.

YD-1 can be operated either with a glass tube installed inside or without glass tube. Figure 1 (upper figures) shows the glass tube inserted in the inner Dewar bottle. The typical glass tube is 70 cm in length consisting of a thin upper part of 60 cm in length with 1.6 cm in diameter and a thick lower part of 10 cm in length with 4.8 cm in diameter. Various sizes of galas tubes were used. The glass tube is connected to an external stainless steel pipe at the flange attached to the inner Dewar bottle. The temperature of the gas in the glass tube is controlled by the cryogenic liquid, liquid helium (<4K) or liquid nitrogen (77K), contained in the inner Dewar bottle. The outer Dewar bottle contains liquid nitrogen (77K) to maintain the inner cryogenic temperature. An rf helium plasma with a neutral gas pressure P = 0.1 ~ 100 Pa is produced by applying the rf (13.56 MHz) power of 1 ~ 7 W between the electrodes mounted in the lower part of the glass tube. The plasma is characterized by the electron density of $n_e \sim 10^{15}$ m^{-3} and electron temperature of a few eV, while ions lose their kinetic energy through collisions with cooled neutrals. Acrylic particles (dust particles) of a = 0.4 ~ 10 μm in radius with a mass density of ρ_d = 1.2 g/cm^3 are dropped from the dust dropper situated about 80 cm high from the bottom of the glass tube. The dust particles charged in the plasma are suspended around an equilibrium position, about a few centimeters from the bottom of the tube, where the upward sheath electric force balances with the downward gravitational force. The particles illuminated by red (λ = 671 nm) or green (λ = 532 nm) laser are visible by naked eyes, while the motion of dust particles are recorded through the slit by a high-speed CCD camera at a frame rate of 200 ~ 400 fps and analyzed by PTV (Particle Tracking Velocimetry) method. To observe vertical motion of dust particles in the plasma, a few particles are dropped from the dust dropper. The dust particles are accelerated in the long glass tube under the gravity. The dust particles are immediately charged after entering the plasma, go further below the equilibrium position and go deeper in the sheath. Electric force acting upward on the charged dust particle in the sheath suspends the dust particle and the dust particle moves upward against gravity.

Figure 1 (lower figures) shows YD-1 without inner tube. Liquid helium is stored in the bottom of the bottle and the vapor pressure is reduced to as low as 0.1kPa to produce a stable plasma. The background neutral temperature is kept to be cryogenic in the presence of the temperature gradient of 3K/cm. A plasma with Te of a few eV is produced by rf voltage (10 kHz, Vpp ~ 6kV, ~1 W) between two horizontal parallel mesh electrodes. Vertical grounded rod electrodes make the plasma diffuse through the electrode toward the surface of liquid helium. T he plasma in the vapor of liquid helium is shown in the right side. Dust particles of 3μm in diameter, dropped from the dust dropper at the top flange, are introduced in the plasma. Forces on a charged dust particle are upward electrostatic and neutral drag forces and downward

gravitational and thermophoretic forces. A movable thermocouple, placed in an acrylic tube with a floating nickel lid, determines the neutral temperature in the diffused plasma. Thermophoretic force is found to play an important role in the dynamics of dust particles in the diffused plasma produced above the liquid helium.

To study the effect of magnetic field on the behavior of microparticles, we installed Helmholtz coil to apply the magnetic field in vertical direction (Fig. 2). Motion of dust particles are controlled by the application of the magnetic field.

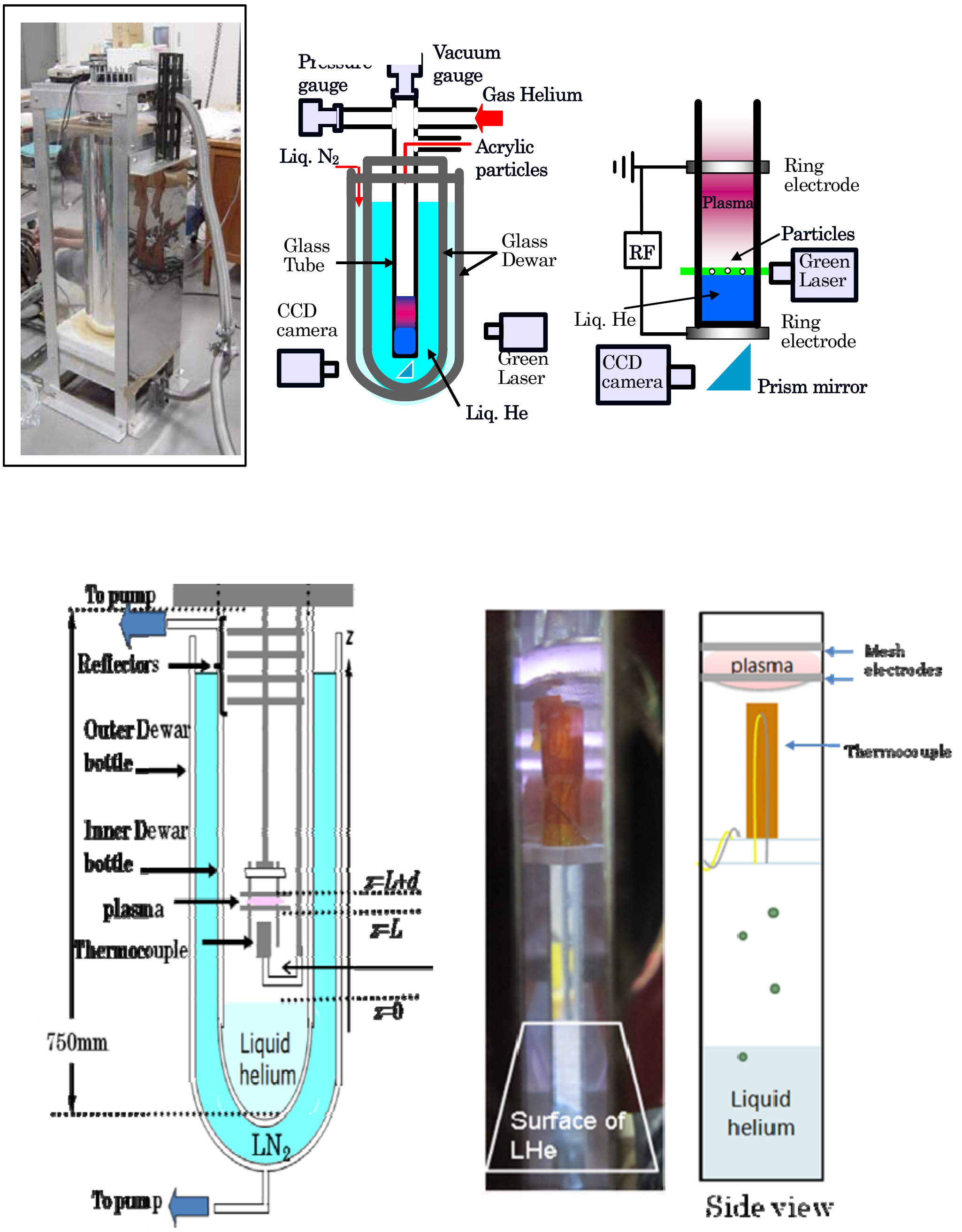


Fig. 1 YD-1 experimental setup. Plasma is produced in an inner tube installed in the Dewer bottle (upper figures) or in the vapor of liquid helium (lower figures).

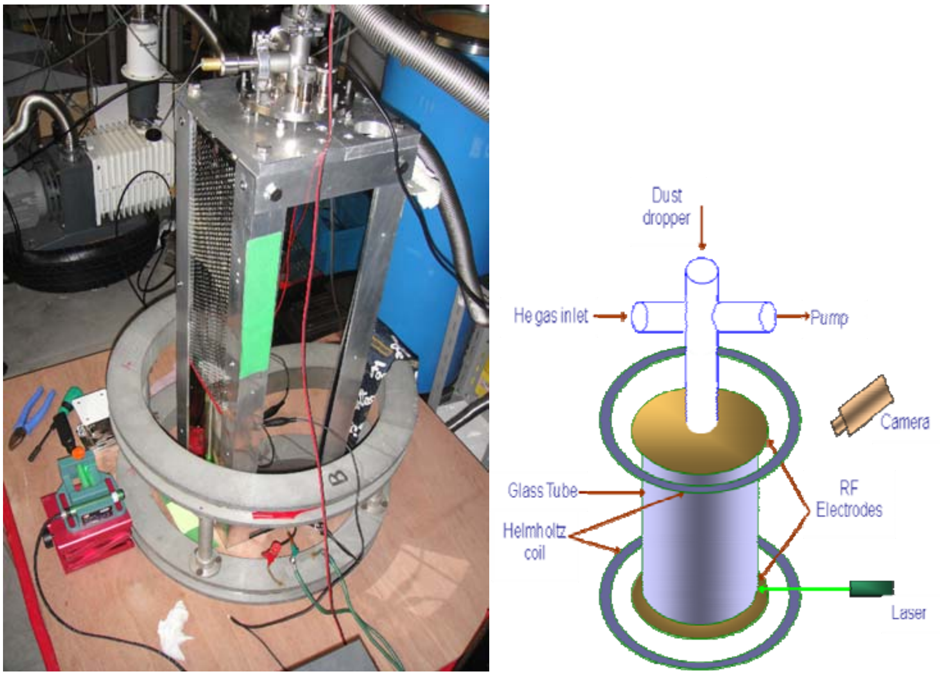


Fig. 2 Helmholtz coil of 25cm in diameter with 135 turns is installed for YD-1. The magnetic field up to 141 G at the current of 30A is measured.

(2) YD-2 Experiment (Publications 2; Presentation 3)

For the purpose of observing the interaction of a plasma and dust particles above the surface of liquid helium, we set up YD-2 (See Fig. 3) and produced a steady plasma above the liquid helium surface. The YD-2 silver-coated Dewar bottle is 16 cm in inner diameter and 1 m in height. The reflectors are installed to avoid external heat flow from the top flange as shown in Fig. 3. The liquid helium is kept in a super fluid state by decreasing the pressure below 0.1 atm. The discharge unit can be moved vertically to adjust the position of the needles from the liquid helium surface. The rf discharge plasma is produced by applying voltage (10kHz, ~6 kV) to tungsten wire needle electrodes. The plasma with neutral density of 10^{26} m^{-3} is produced locally near the electrodes in high gas pressure (6 ~ 8 kPa). Dust particles are introduced from the upper part of the Dewar bottle. Dust particles dropped from the dust dropper near the flange are gaining enough energy under the gravity before reaching the plasma region. Once dust particles are in a plasma, dust particles are charged and continue to move downward away from the plasma. Then charged dust particles enter the region of liquid helium vapor where two parallel plates produce electric field in the horizontal direction. The trajectories of charged dust particles are deflected by the electric field and are recorded by a CCD camera. We observed decharging process of dust particles by detecting the trajectories of dust particles coming out of the plasma in a cryogenic environment. Although dust charges decrease in cryogenic environment, they still have enough charges to form crystals and to float on the liquid helium surface if particles are light weighted such as glass hollow particles.

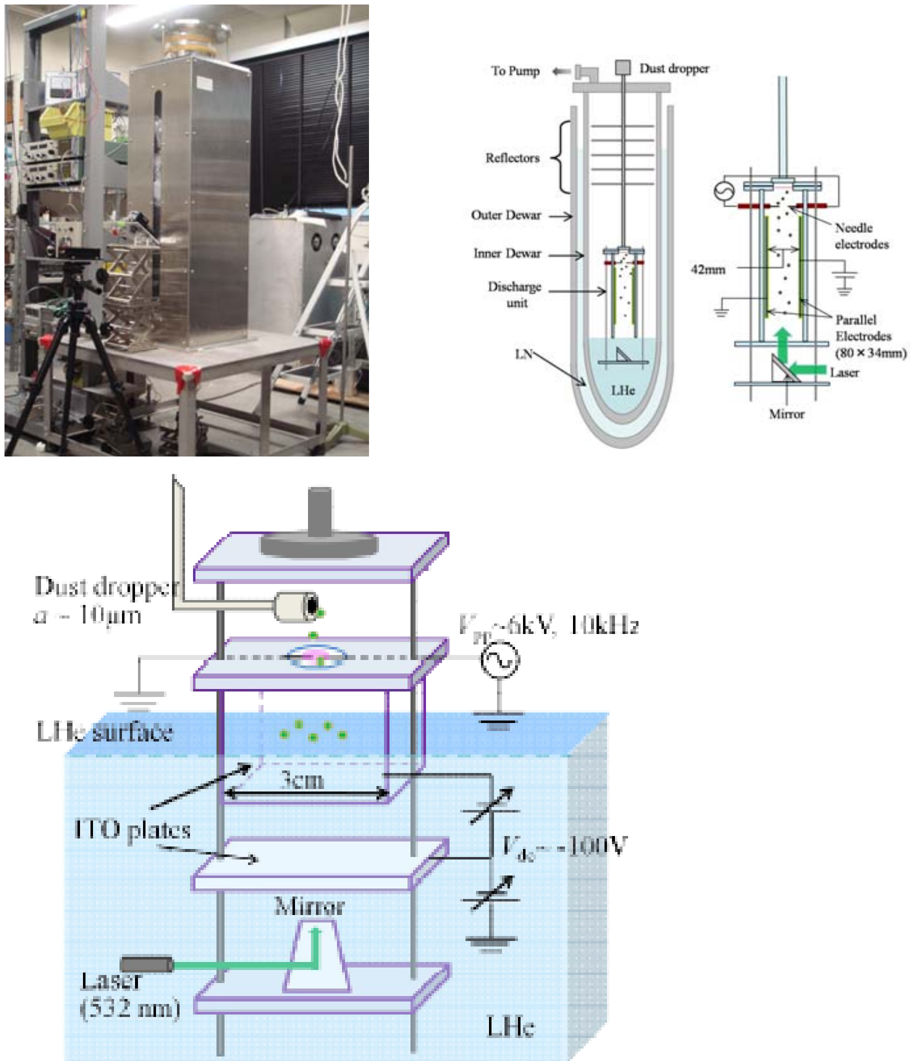


Fig. 3 YD-2. Plasma is produced in a vapor of liquid helium. Dust charges are measured just above the liquid surface.

(3) YD-3 experiment (Presentation 8)

YD-3 is installed to observe dust particles on the surface of liquid helium through a large observational window (Fig. 4). The YD-3 is much smaller than YD-1 and YD-2 in a volume of liquid helium. Particles charged in the plasma are observed dropping in the liquid helium (~1.4K) stored in YD-3 device. Some particles fall between the parallel electrodes immersed in LHe, where 100V between 13mm is applied. The falling velocity of the particles in LHe is at about 5mm/sec. Dust particles dropped from the dust dropper are pushed by He gas through the plasma into the observation area. The quantity of the helium gas is controlled by the volume (~2cm^3) and the gas pressure (~0.01MPa).

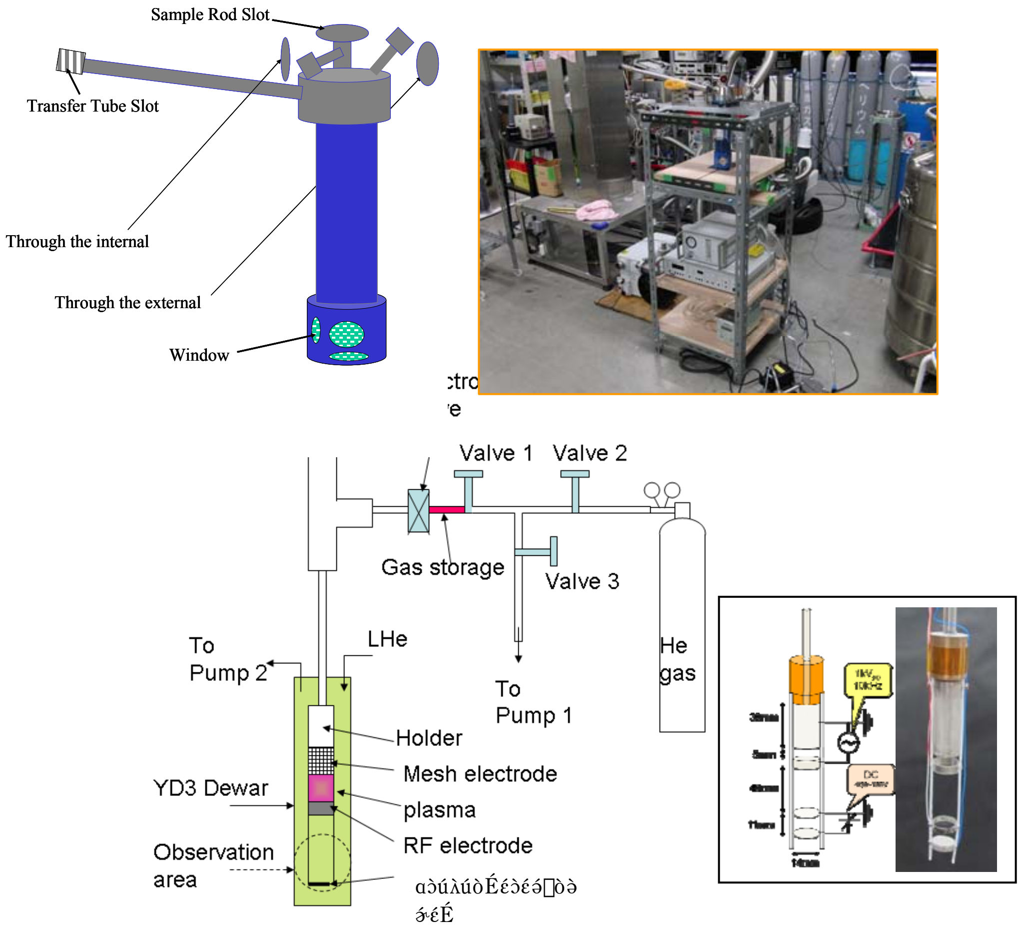


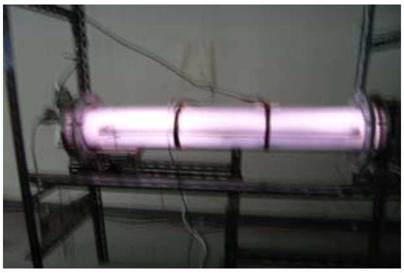
Fig. 4 YD-3. A small Dewar bottle which keeps little liquid helium

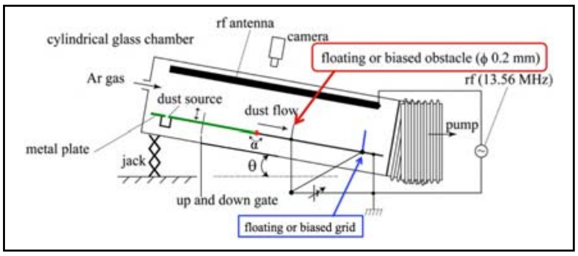
(4) YCOPEX (Publications 4,6; Conference proceeding 3; Presentation 4,5,7)

The Yokohama complex plasma device (YCOPEX) is shown in Fig. 4. The Pyrex glass tube (G) is 100cm in length and 15cm in inner diameter. In the figure, the tube is connected to the bellows (B) at the left end. A stainless steel plate(P)(2mm in thickness) of 14.8cm in width and 90cm in length is placed in the middle of the tube along the axis. Two piezo-electric buzzers (Z) are set under the plate at 5cm from the edge of the plate. Silica micro-particles of 5 μm in diameter and the density of 1.6g/cm^3 are contained in the buzzers. The hole of 1mm in diameter is made over each buzzer. Several spherical plastic beads of 1.5mm in diameter are also contained in the buzzers to shatter the powders to pieces if they are coagulated together. When the dc voltage of 0-10V is applied to the buzzers, they oscillate with a frequency of 2 kHz so that micro-particles jump up from the holes. At both edges of the plate, two

stainless steel foils (F) of 0.1mm in thickness and 2cm ≃ in height are placed as fences to confine particles longitudinally. Particles are radially confined by the ion-sheath formed in front of the surface of the glass tube.

A bow shock is observed in a two-dimensional supersonic flow of charged mi cro-particles in a complex plasma. A thin conducting needle is used to make a potenti al barrier as an obstacle for the particle flow in the complex plasma. The flow is gene rated and the flow velocity is controlled by changing a tilt angle of the device under t he gravitational force. A void, microparticle-free region, is formed around the potenti al barrier surrounding the obstacle. The flow is bent around the leading edge of the v oid and forms an arcuate structure when the flow is supersonic. The structure is chara cterized by the bow shock as confirmed by a polytropic hydrodynamic theory as well as numerical simulation.





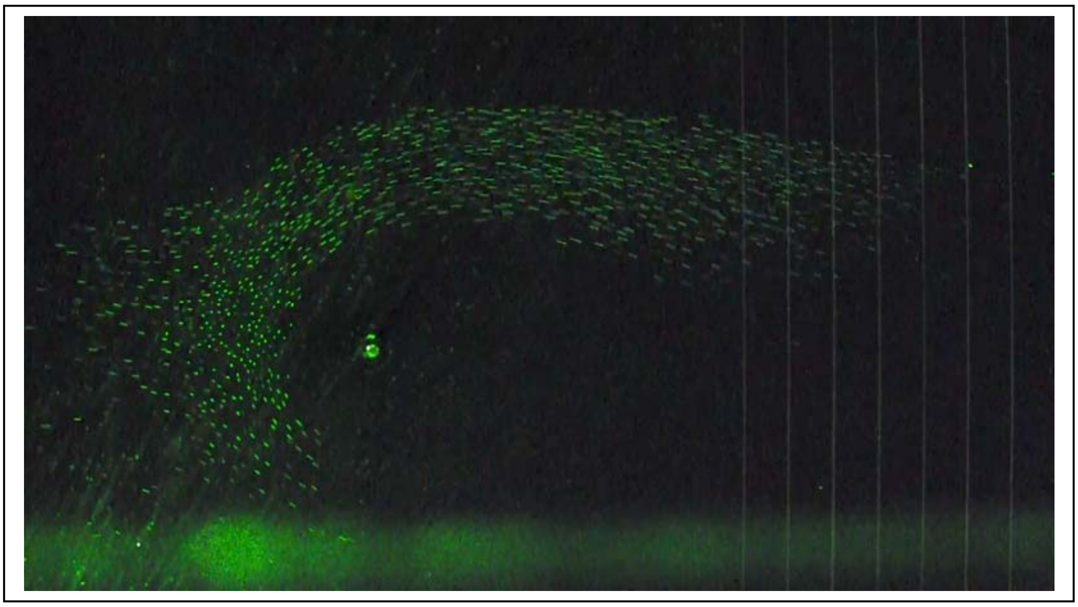


Fig. 5. YCOPEX. Linear device for the room temperature complex plasma. A dust cluster floats above the sheath. Individual microparticles are visible through the illumination of green laser.

Results

(1) Theoretical study on charging mechanism of dust particles in a nonuniform discharge plasma under cryogenic environment revealed the plasma density and temperature effects on dust grain charging. The charge at a cryogenic temperature is found to be much smaller than that at the room temperature, in agreement with our experimental observation. It is suggested that charged dust grains at cryogenic temperature makes the formation of a strongly coupled system of dust particles.
(2) Cryogenic plasma experiments in YD-1 and YD-2 accumulated information on chargin g of microparticles in the vapor of liquid helium.
(3) Large area complex plasma device was used to study shock formation especially to st udy bow shock formation in the presence of potential barrier.
(4) Analytical and computational study revealed the formation of double helix of microparticles confined in a prolate spheroidal potential in a complex plasma.

Microparticles in a complex plasma are visible by naked eyes and help us to understand fundamental nature of physics principles.

List of Publications:

a) papers published in peer-reviewed journals,

1. Wataru Sekine and Osamu Ishihara, Cryogenic effect on dust grain charging in a plasma, Journal of Plasma and Fusion Research Series **9**, 416-421 (2010).
2. Natsuko Uotani, Jumpei Kubota, Wataru Sekine, Megumi Chikasue, Masako Shindo and Osamu Ishihara, Dust Charging in Collisional Plasma in Cryogenic Environment, Journal of Plasma and Fusion Research Series **9**, 404-409 (2010).
3. T. Kamimur, O. Ishihara and Y. Suga, Stable helical structure of Coulomb cluster, Research Reports of the Faculty of Science and Technology, Meijo University, Nagoya Japan **51**, 19 (2011). (in Japanese)
4. T. Kamimura, and O. Ishihara, A. Seto, H. Yonezawam, Y. Saitou and Y. Nakamura, 'Formation of bow shock in dust flow in a pplasma,' Research Reports of the Faculty of Science and Technology, Meijo University, Nagoya Japan **51**, 29 (2011). (in Japanese)
5. O. Ishihara, Advances in Various Fields of "Plasma and Dust Particles, J. Plasma and Fusion Research) Vol. **86**, 79-81 (2011) (in Japanese)

b) papers published in non-peer-reviewed journals or in conference proceedings,

1. M. Chikasue, M. Shindo and O. Ishihara, Thermophoretic force on charged dust particles in cryogenic complex plasma, Sixth International Conference on Physics of Dusty Plasma (ICPDP6) (Garmisch-Partenkirchen, Germany, May 16-20, 2011)
2. N. C. Adhikary and O. Ishihara , Dust cluster rotation in cryogenic magnetized plasma, Sixh International Conference on Physics of Dusty Plasma (ICPDP6) (Garmisch-Partenkirchen, Germany, May 16-20, 2011) .
3. O. Ishihara, Y. Nakamura, Y. Saitou and T. Kamimura, Observation of Bow Structures in a Complex Plasma, Sixh International Conference on Physics of Dusty Plasma (ICPDP6) (Garmisch-Partenkirchen, Germany, May 16-20, 2011) .

c) conference presentations,

1. M. Chikasue, N. Adhikary, N. Uotani, C. Sekino, M. Shindo and O. Ishihara, Study of thermophoretic force on a dust particle in collisional cryogenic plasma, 11th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Nov. 19-20, 2010).
2. N. C. Adhikary, Y. Nakamura and O. Ishihara, Determination of ion temperature from rotating dust cluster in the presence of magnetic field in a plasma, 11th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Nov. 19-20, 2010).

3. N. Uotani, M. Chikasue, T. Wakiya, C. Sekino, M. Shindo and O. Ishihara, Behavior of charged dust particles on the liquid helium surface, 11th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Nov. 19-20, 2010).
4. Y. Saito, Y. Nakamura and O. Ishihara, Confinement of charged dust particles in a dc discharge plasma toward the space plasma study, Space Plasma Research Conference (JAXA, Sagamihara, 2011.3.3-3.4) (in Japanese)
5. Y. Nakamura, N. Toma, Y. Saito, and . O. Ishihara, Dust acoustic wave in a complex plasma, Space Plasma Research Conference (JAXA, Sagamihara, 2011.3.3-3.4) (in Japanese)
6. M. Chikasue, M. Masuda, M. Shindo and O. Ishihara, Spatial diffusion of dust particles charged in a plasma at cryogenic condition, PLASMA2011 (Kanazawa, Nov. 22-25, 2011) Submitted.
7. Y. Saito, Y. Nakamura, O. Ishihara and T. Kamimura, Bow shock formation in a complex plasma PLASMA2011 (Kanazawa, Nov. 22-25, 2011) Submitted.
8. M. Shindo, M. Chikasue, H. Wakiya and O. Ishihara, Interaction between dust particles charged in a plasma and electrons on liquid helium surface, PLASMA2011 (Kanazawa, Nov. 22-25, 2011) Submitted.
9. Y. Hayashi, K. Koga, T. Mieno, K. Takahashi, A.Nakamura and O. Ishihara,, Advances in Fine Particle plasma science, PLASMA2011 (Kanazawa, Nov. 22-25, 2011) Submitted.

d) manuscripts submitted but not yet published

1. Y. Saitou, Y. Nakamura, T. Kamimura, and O. Ishihara, Bow shock formation in a complex plasma. (submitted to Physical Review Letters)
2. Tetsuo Kamimura and Osamu Ishihara, Coulomb Double Helical Structure. (submitted to Physical Review Letters)

e) patents that resulted from this work.

N/A